An Overview of Alternative Remediation Methods
for Groundwater Contamination

by

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ABSTRACT

Cleaning up groundwater resources contaminated by the infiltration of various chemicals used by man and various waste products generated by human activities is a problem of major importance facing hydrogeologists today. The following paper presents discussions of current technology and methods used in the remediation of groundwater contamination to serve as guidelines for decision making in aquifer restoration projects. By citing case histories involving groundwater contamination and subsequent product recovery, groundwater treatment, and aquifer restoration, problems and solution methods are demonstrated.

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INTRODUCTION

There are three major problems associated with groundwater use: 1) overdraft, 2) water rights/ownership, and 3) contamination (Davis, 1983). Of the three, groundwater contamination is the problem which has received the greatest attention over the past several years. Water users, as well as state and federal regulatory agencies have recognized a need to prevent pollution of the nation's groundwater resources in order to protect human and animal health (Heath, 1983). Groundwater is used in two principal ways, for human, agricultural and industrial consumption; and for the transportation of waste products. The transportation of wastes results in a cumulative degradation of water quality tempered somewhat by the natural filtration and adsorption provided by aquifers (Fried, 1975). Groundwater contamination may be defined as a modification of the physical, chemical, and biological properties of groundwater, restricting or preventing its use in the various applications where it normally plays a part (Fried, 1975). The impacts of contamination on groundwater may range from aesthetic effects (such as unpleasant taste or warm temperature) to imminent hazards to health (Davis, 1983).

Groundwater pollution originates from many different sources, the three most common ones being industrial wastes,

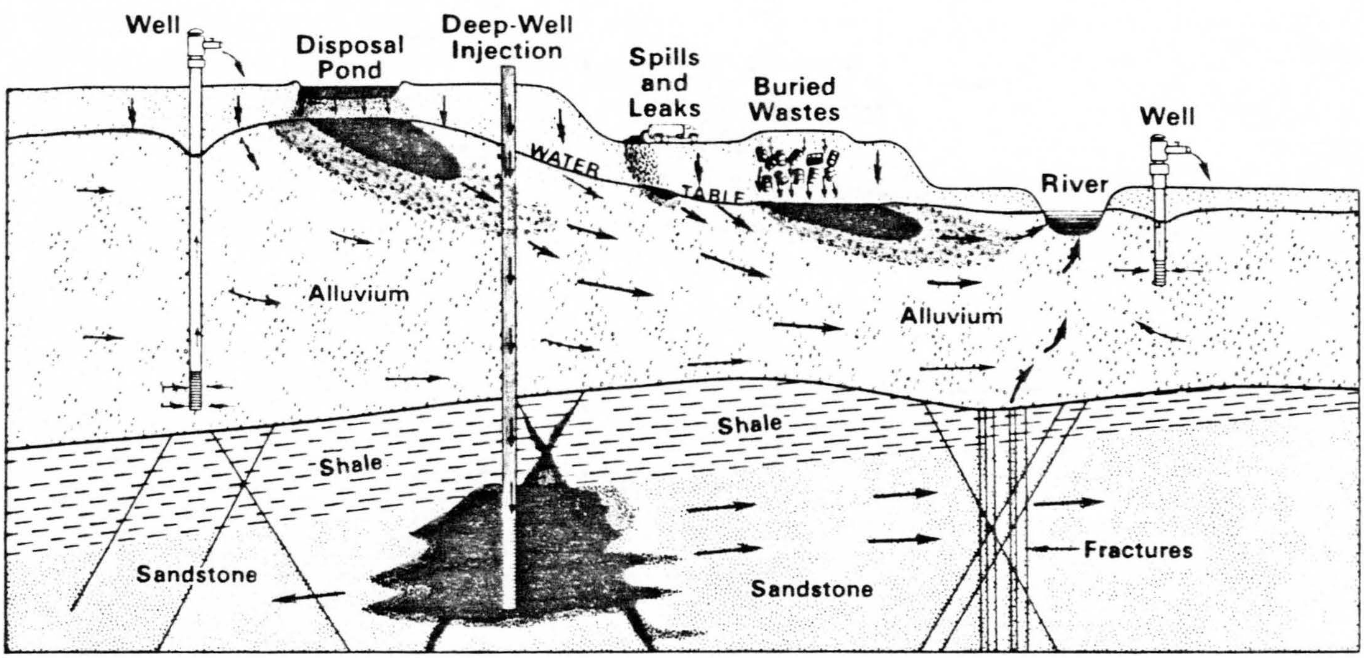

Figure 1. Schematic diagram of industrial waste disposal methods (Davis, 1983).

municipal landfills, and agricultural chemicals (Davis, 1983). Each source of pollution presents a set of problems unique to each particular site. Figure 1 illustrates several different ways in which industrial wastes are disposed of and how contaminants can make their way into groundwater supplies.

The amount of potentially dangerous toxic industrial wastes is alarming. By 1981, the inventory of toxic wastes was 6 billion cubic yards at 100,000 sites in the U.S. (Davis, 1983). The threat of these toxic materials to health depends upon factors such as the geology of the site and the character of the wastes.

The very nature of groundwater (it flows unseen, movement is often very slow, and it may react chemically and physically with contaminants retarding their movement) often makes it impossible to detect contaminants until they have reached water-supply wells. In most cases, once aquifers have been contaminated, cleanup is costly and time consuming.

In order to conduct an aquifer rehabilitation project, whether it is an emergency response to a chemical spill, cleanup of an uncontrolled hazardous waste dump, or cleanup of a municipal landfill, the first step is the collection of background information about the site. A preliminary investigation using conventional drilling and sampling and/or geophysical methods entails the gathering of hydrogeologic, geologic, and geochemical data for the contamination site under study. Following, or concurrent with the preliminary investigation, hydrodynamic and/or physical methods of isolating the contaminants to prevent further migration into pollution-free groundwaters must be implemented. Another essential step in aquifer restoration is product recovery. It is accomplished through gravity collection methods or by recovery wells to facilitate re-use or proper disposal of the product.

Aquifer restoration refers to the restoration of polluted groundwater to its normal quality, usually by removing both the source of pollution and renovating the polluted groundwater (Canter and Knox, 1985). To accomplish complete renovation of an aquifer, contaminated groundwater requires some type of treatment in addition to removal of pollutants from the aquifer itself. Treatment techniques consist of air stripping, carbon adsorption, biodegradation, and in-situ natural treatment. Of course treatment is meaningless unless a source (or sources) has been pinpointed and abated. Abatement refers to application of techniques which will aid in preventing pollutant migration into groundwater, or preventing contaminant plume movement into usable aquifer zones (plume management) (Canter and Knox, 1985). Finally, in any remedial action project, groundwater monitoring of the site is crucial. Monitoring provides all the essential information on site conditions and contaminant-plume movement needed to evaluate and implement effective aquifer-restoration methods.

There is a critical need to identify and manage contamination sites both from the standpoint of protecting public health and preserving the resource (Miller, 1984). Although methodologies for recovery and treatment of contaminated groundwater are well established, the application of specialized techniques and equipment to real situations has been limited (Quince and Gardner, 1982). In this paper, a discussion of procedures and methods used in groundwater pollution control is presented with the intention of showing that although their application will undoubtedly require modifications depending upon conditions at a given site, they can serve as guidelines for decision making in remedial action projects.

PRELIMINARY INVESTIGATION

Following the occurrence of a groundwater contamination incident, an understanding of the movement of pollutants in the subsurface is essential. Conditions may vary considerably at different waste or spill sites, therefore, a site-specific preliminary investigation is absolutely necessary at the start of any groundwater restoration project. The successful abatement of any groundwater contamination problem is always a function of how comprehensively it has been assessed and how well it is understood (Yaniga, 1982).

The purpose of a site assessment or investigation is to determine the extent and nature of contamination and to identify subsurface conditions so that proper remedial steps can be taken. The geology, hydrogeology, and contaminant characteristics, as well as their interrelationships must be understood. In many situations, information from previous investigations will be already available. Existing wells also might prove useful in delineating the contaminant plume.

The existence of records for waste dumps might provide clues as to the amounts and types of wastes present at a site. In general, a preliminary survey consists of the collection and review of soil data, geologic reports, groundwater-resource

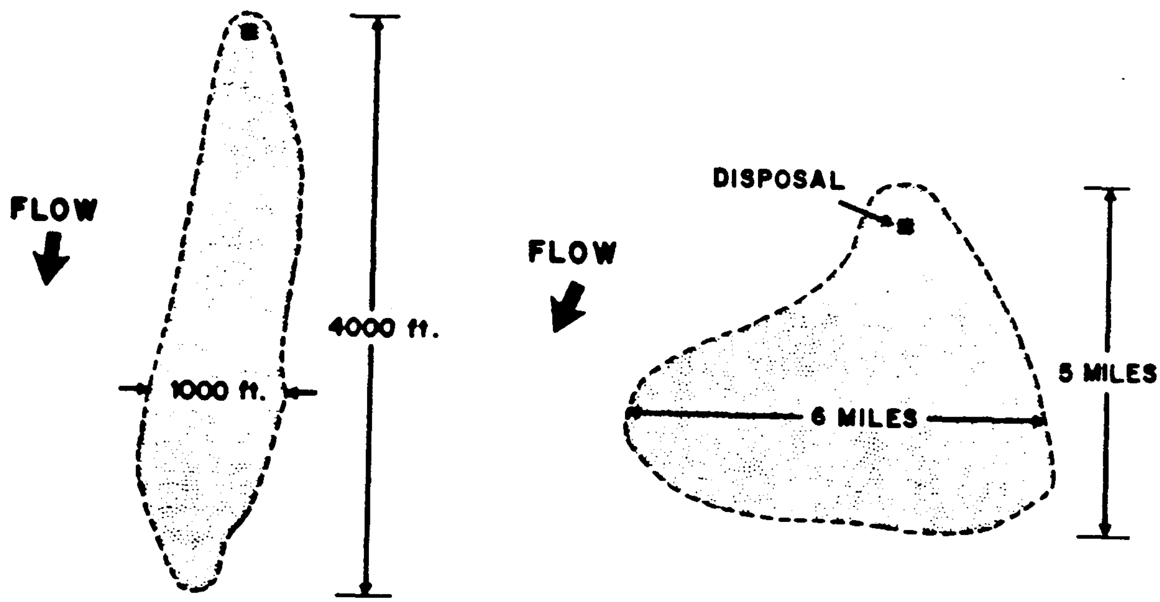

Figure 2. Effect of differences in geology on the shape of contaminant plumes. A. Chloride plume, basalt aquifer. Time: 16 yrs. B. Chromium plume, sand and gravel aquifer. Time: 13 yrs. (Miller, 1984).

reports, test-boring data, well logs, and water-quality data for the site vicinity.

Data obtained from a site-specific study may indicate whether a site overlies an important aquifer, the depth of the aquifer, the general direction of groundwater flow, the ambient water quality, and the presence of other water-bearing strata (Miller, 1984). Quince and Gardner (1982) list formation porosity, permeability, hydraulic gradient, groundwater velocity and direction, and recharge/discharge data as essential hydrogeologic information useful in predicting contaminant plume movement. The prediction of plume movement depends upon the physical and chemical nature of the con-

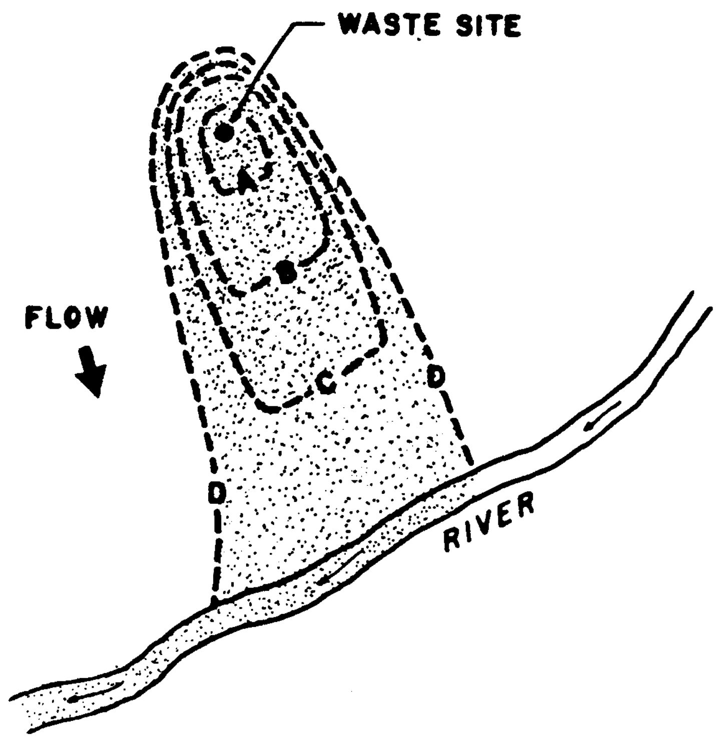

Figure 3. Schematic diagram showing areal extent of contamination by specific contaminants A, B, C, and D in a mixed-waste plume (Miller, 1984).

taminant and its attenuation and migration within the aquifer.

Test drilling is an essential part of any preliminary investigation. A number of exploratory drillings are usually required before geologic, hydrologic, and geochemical conditions are known (Miller, 1984). When drilling, the method used should take into account sampling needs. For instance, if undisturbed soil samples are needed, mud-rotary drilling would not be recommended. Instead, a hollow-stem auger would give better results by eliminating the need for drilling mud. Test-drilling methods used also depend upon soil/rock types, depth-to-water, and contaminant type.

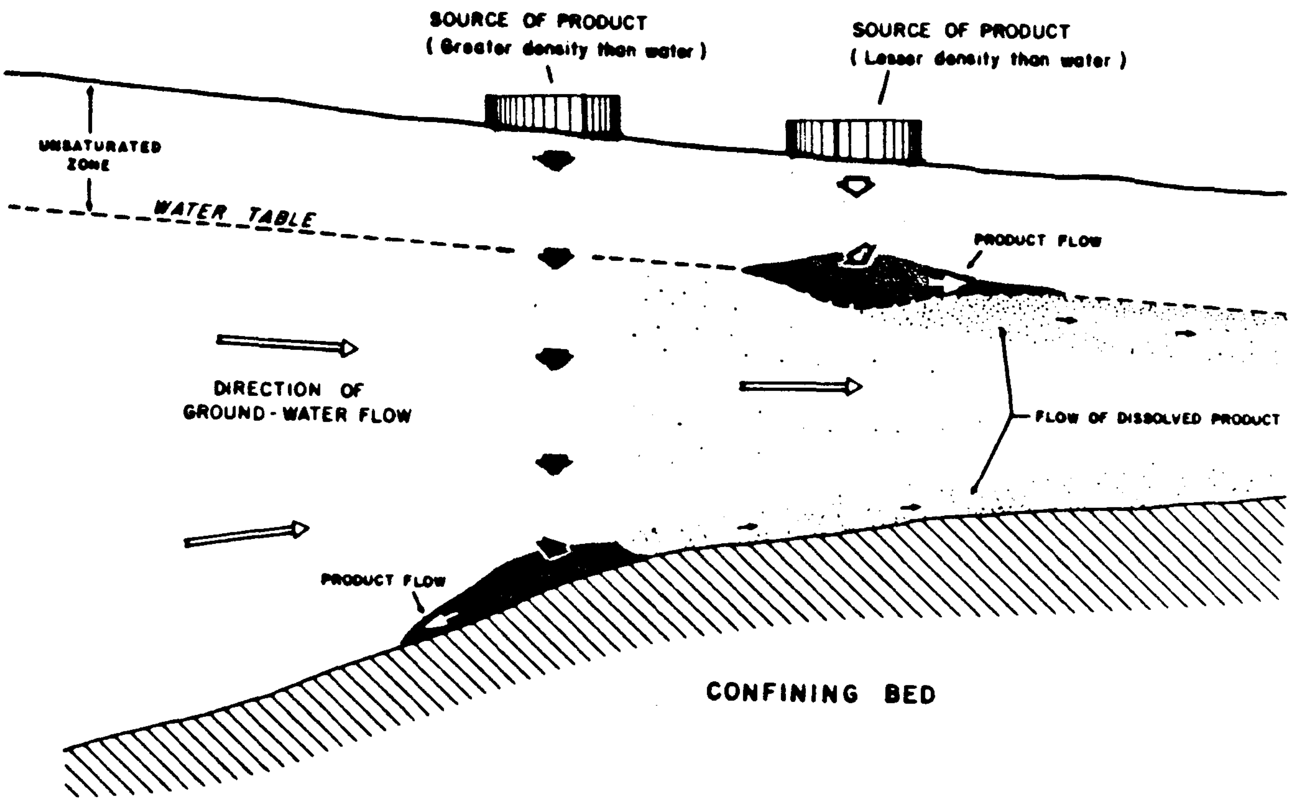

Figure 4. Effects of density on migration of contaminants (Miller, 1984).

The aquifer geology, its porosity and its permeability affect the movement of contaminants in the subsurface. As shown in Figure 2, the different characteristics of a basalt aquifer resulted in a much different plume shape than that of a sand and gravel aquifer. The size and shape of a contaminant plume also is dependent upon the physical and chemical nature of the pollutants.

A waste site which contains several types of chemicals will exhibit variation in the extent of plumes with respect to chemical type (Figure 3). Multiple plumes occur beneath waste sites due to multiple contaminants or due to a contaminant having several components. Differences in migration rates caused by differences in contaminant chemistry result in formation of several plumes. Organic plumes (A in Figure 3) tend to be retarded more in an aquifer when compared to a chloride (Cl^-) plume (D in Figure 3) because the chloride travels at normal groundwater velocities, whereas organic contaminants tend to be attenuated.

The density of contaminants in relation to the density of water will determine their flow paths in the subsurface. Those materials with a density greater than water will migrate downward until they reach a confining layer, whereas those less dense than water (gasoline) will float on top of the water table. Figure 4 illustrates the behavior of products with varying densities as they enter the groundwater flow system. As discussed in subsequent sections, this greatly affects the method of product recovery chosen as well as correct monitoring well placement.

Contaminants in the subsurface manifest themselves in several ways. They may occur as free product, as dissolved or emulsified products in groundwater, or as vapors in the unsaturated zone and in soils. Figure 5 illustrates

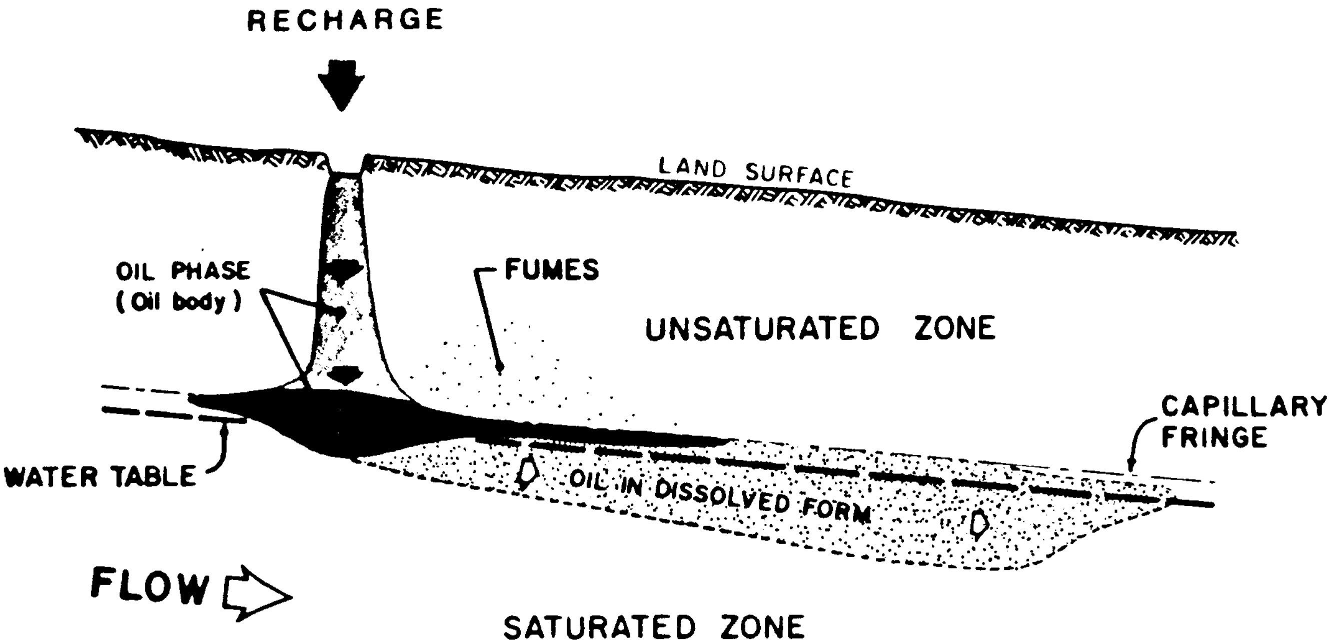

Figure 5. Petroleum product reaching groundwater (Miller, 1984).

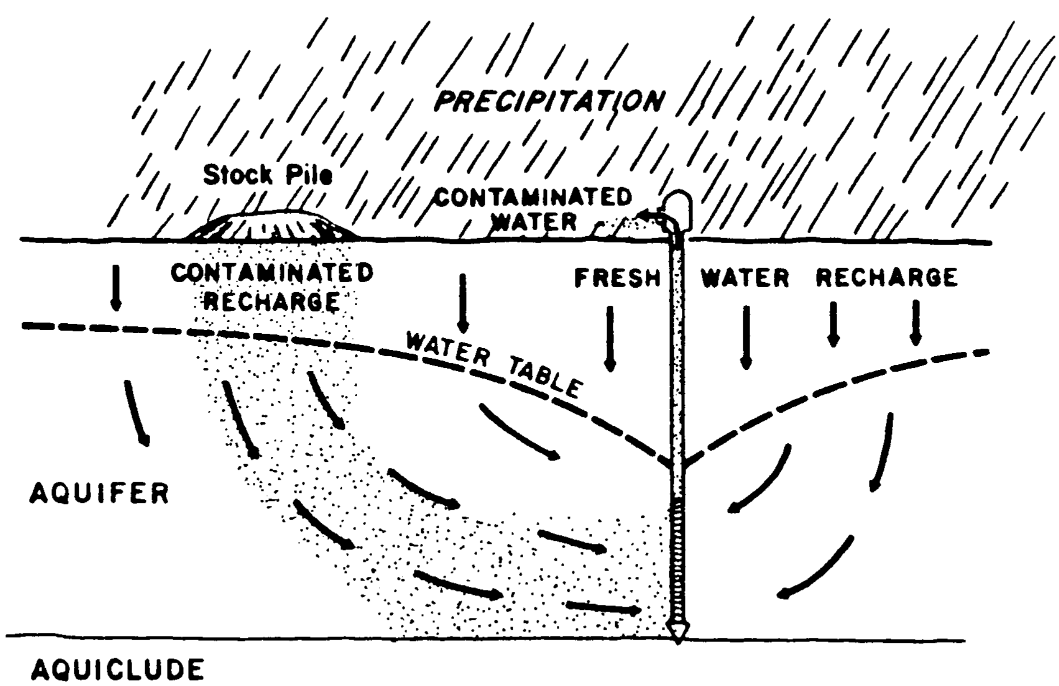

Figure 6. Influence of a pumping well on plume migration (Miller, 1984).

the behavior of petroleum in an aquifer.

Another factor affecting the movement of contaminants in groundwater is the presence of pumping wells. When near a contaminated site, they can alter the flow paths and flow rates of pollutants which enter into the cone of influence of a well (see Figure 6). The effects of withdrawal and recharge wells on plume migration may, however, be put to good use in the management of contaminant plumes. Techniques of hydrodynamic isolation are described in a later section.

Due to the potential danger of punctures, explosions, gas leaks, and other dangers at hazardous-waste-disposal sites, only peripheral data can be obtained by conventional drilling or excavating (Knowles and others, 1982). Other data-gathering techniques need to be employed if one is to properly evaluate the extent and quantity of wastes and the geologic environment with which that waste is in contact. Geophysical techniques offer a feasible, non-destructive alternative to conventional destructive exploration methods. Four techniques in common use are outlined by Knowles and others (1982). They are earth resistivity, magnetometer surveys, groun-penetrating radar, and seismic refraction.

Earth resistivity measures the apparent resistance of earth materials to an electric current. To identify different strata beneath the ground surface, measured resistivity values are compared with known ranges of resistivity of certain earth materials. Earth resistivity may be applied to contaminant plume investigation and plume tracking. The technique is used to identify leachate plumes based on the principle that contaminated groundwater or leachate has a high conductance (the inverse of resistivity) due to the presence of dissolved solids (Knowles and others, 1982).

Magnetics is another geophysical method used in site evaluation. This method utilizes the total magnetic field intensity of a media to determine the presence of metallic objects. Although depth cannot be accurately determined, this method has been used successfully to locate buried drums and pipelines. There is the advantage of also being able to use a magnetometer in any terrain.

Ground-penetrating radar is utilized to measure depths and detect discontinuities in the subsurface by reflection of short-duration electromagnetic pulses radiated into the ground. The chief advantage of ground-penetrating radar is that it can provide a continuous profile of the subsurface with the use of easily portable equipment. This technique is fairly new and sophisticated, therefore it is a relatively costly alternative in groundwater studies.

Seismic refraction relies on the physical principle that the time of passage of elastic compression waves through the ground can be recorded over a measured distance. Shock waves travel through different media at different velocities and by interpreting these velocity differences, different strata can be identified. To create the shock waves, small explosives, dropped weights, and sledgehammers are used. Data obtained in seismic studies include depth to bedrock and vertical limits of a disposal site. This technique is ideally suited to sites where drilling might be dangerous.

The direct application of these geophysical techniques at a hazardous-waste site has been documented by Knowles and others (1982). The waste-disposal site, operational from the 1950's through 1970, contained chlorinated solvents, waste oils, PCB's, scrap materials, and solid waste. It covered an area of 11 acres, 6 of which were waste lagoons; the remainder were drum and miscellaneous disposal areas. By using geophysical methods, the investigators sought to determine contaminant migration pathways, and ultimately to develop a remedial program for abatement of the waste materials. Of the four techniques considered, only ground-penetrating radar, the magnetometer, and seismic refraction were used.

A magnetometer survey determined the horizontal extent of buried drums and the location of suitable sites for drilling wells. Ground-penetrating radar also was attempted, however, available equipment did not achieve desired depths of penetration. The seismic refraction method, along with test borings, yielded useful cross sections of the geology beneath the site. One of the primary benefits of the combined magnetometer and seismic surveys was the determination of the location of 11 test borings, approximately half the number that would have been drilled had geophysical data not been available. This reduced costs and saved time during the site investigation. The geophysical techniques used in this investigation represent non-destructive methods designed to aid in the definition of the vertical and horizontal limits of a hazardous-waste site, assist in the determination of subsurface geophysical characteristics, and locate with relative accuracy the probable sources and pathways of contamination within, beneath, and adjacent to the disposal site (Knowles and others, 1982).

CONTAINMENT OF CONTAMINATED GROUNDWATER

Once the extent and character of the contaminant plume are known, the appropriate containment procedure is chosen and implemented. Methods for containment of contaminated groundwater fall under two main categories: Hydrodynamic isolation and physical containment methods. Physical barriers include slurry walls, sheet-pile cutoff walls, grout curtains, surface capping, and liners. Physical barriers are used to create impermeable boundaries to groundwater flow. Hydrodynamic isolation or gradient reversal techniques are accomplished either by withdrawal or by artificial recharge of groundwater. The basic premise behind hydrodynamic isolation lies in the creation of a closed system within which a discrete zone of groundwater is isolated and recirculated from pumping wells to recharge wells and/or trenches. As such, the isolated groundwater may be considered to be an impermeable zone within a larger, regional flow regime (Ozbilgin and Powers, 1984).

The objective of hydrodynamic isolation in hazardous waste sites is to contain a significant portion of the highly contaminated plume (Ozbilgin and Powers, 1984). Ideally, a hydrodynamic isolation system should be used in conjunction with treatment facilities so that treated groundwater is returned to the ground. Figure 7 illustrates the use of withdrawal wells to limit migration of contaminated ground-

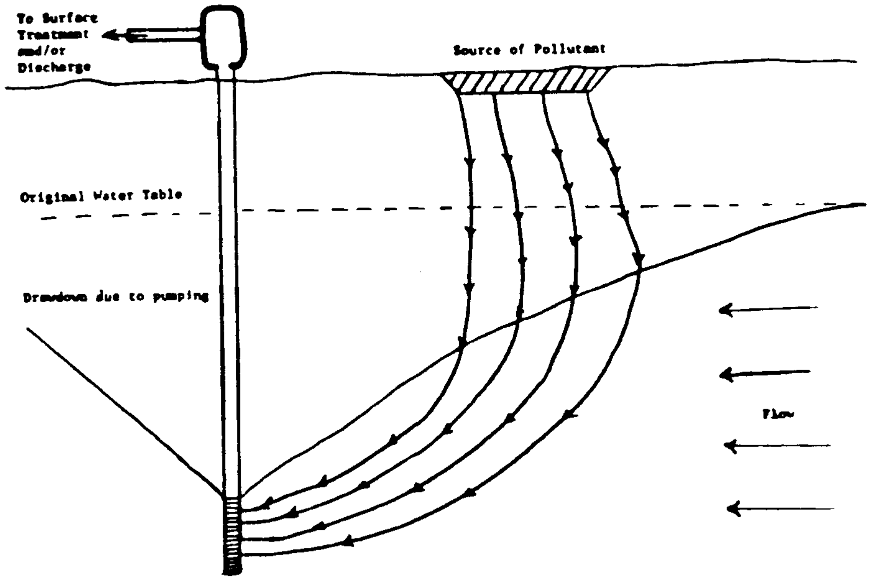

Figure 7. Principle of withdrawal wells (Canter and Knox, 1985).

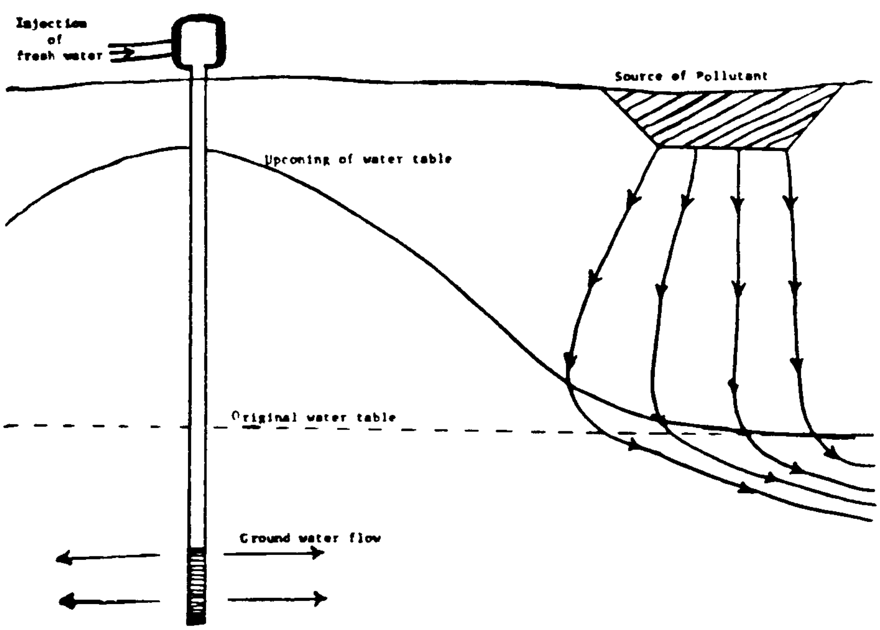

Figure 8. Principle of pressure ridge system (Canter and Knox, 1985).

water. The drawdown in the well created by pumping diverts the flow path of contaminants. The contaminated groundwater is withdrawn then transported to treatment systems or used to recharge the aquifer forming a closed hydrodynamic loop to await implementation of final remedial measures. This closed-loop system prevents further plume migration resulting in effective containment of pollutants.

Hydrodynamic control of groundwater pollution also may be achieved by creating a pressure ridge with injection wells (Figure 8). By reversing the hydraulic gradient, pollutants are forced away from a given area to enable withdrawal and treatment elsewhere. Recharge techniques are effective where the contaminants are immiscible and float on the water-table surface. The product is raised closer to the ground surface where recovery is made easier (Glover, 1982).

An aquifer restoration project described by Ozbilgin and Powers (1984) consisted of a groundwater recirculation system comprising five pumping wells and an upgradient recharge trench used to temporarily retard the advance of a highly contaminated plume at a site polluted by volatile organics. After further study, it was found that a network of pumping wells combined with a slurry cutoff wall could reduce the previous 55,000 gallons per day of contaminated groundwater being discharged into streams to less than 6,000 gallons per day.

Physical containment of contaminated groundwater utilizes several methods which have been described by Glover (1982).

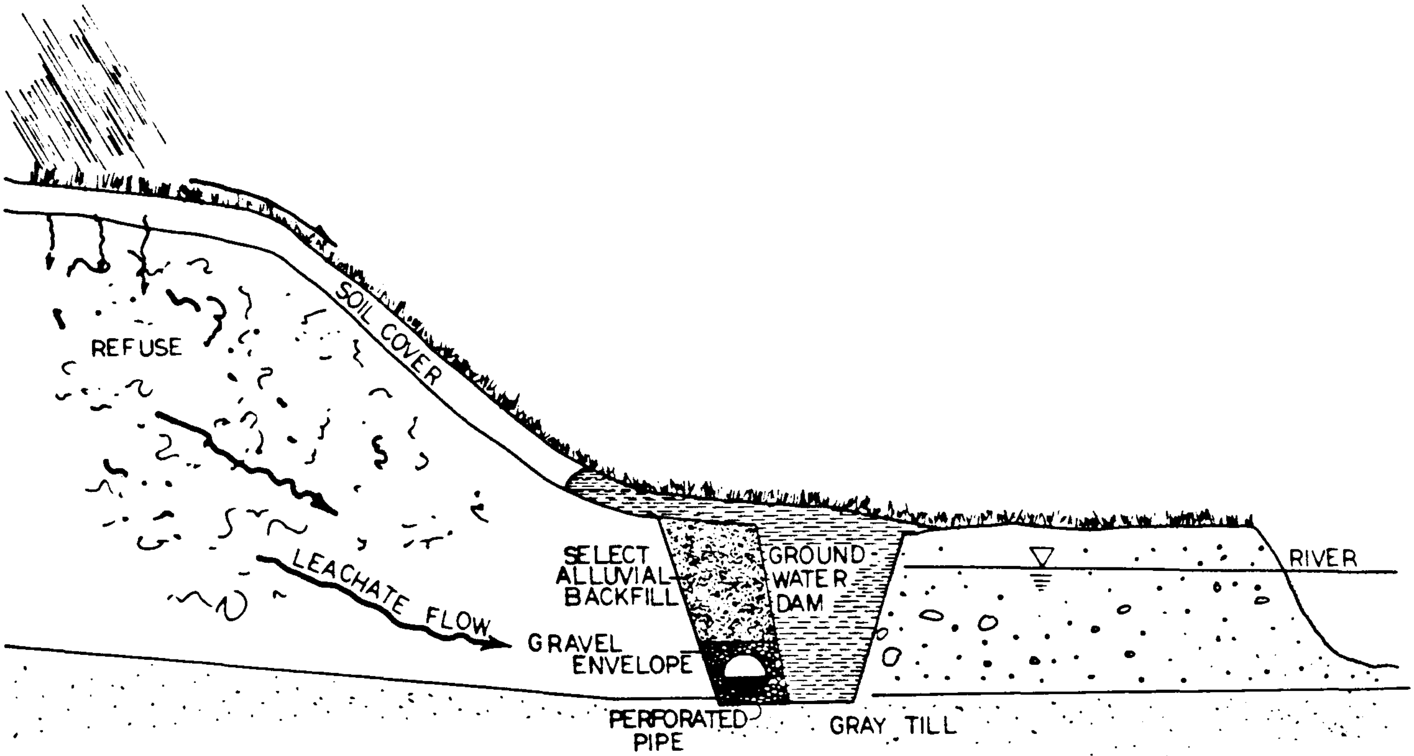

Figure 9. Site cross section of a groundwater dam used to contain leachate at a landfill (Giddings, 1982).

These methods include slurry walls, vibrated beams, grout curtains, sheet-pile cutoff walls, surface capping, and lining. Another method, the groundwater dam (Figure 9), has been described by Giddings (1982).

Construction of a slurry wall begins with the excavation of a trench around the spill site into an impervious layer to provide confinement beneath the site. As excavation into the unconsolidated materials proceeds, a viscous bentonite slurry is pumped into the trench. The trench is subsequently backfilled with native soils which have been mixed with bentonite.

Effective containment has been achieved to depths of over 100 feet (Glover, 1982).

A variation of the slurry-wall system, the vibrated beam method uses a specially adapted I-beam which is vibrated into the ground to the desired depth and then withdrawn. As the beam is withdrawn, a slurry mixture is injected through nozzles at the tip of the beam maintaining a positive pressure on the sides of the trench. The process is repeated around a site to create a slurry-filled trench 4 inches wide. Used to depths of up to 80 feet, it is most effective in loose, unconsolidated materials (Glover, 1982).

Another common method of physical containment is the grout curtain which is usually used only in bedrock. Grout pipes are driven into the rock and a chemical or cement is injected through them at high pressure, then the pipes are withdrawn. After a group of grout-filled holes has been completed around a site, a second set of holes is placed between the first set. The process is repeated until an impervious seal is formed around the spill. It is a slow, expensive process but it can be used in confined areas with relatively simple equipment (Glover, 1982).

Sheet-pile cutoff walls are constructed by driving interlocking sheet piles into unconsolidated materials around a contaminant spill until reaching an impervious strata below. Interlocking sheet piles seldom form a watertight seal, however, they can reach depths of up to 100 feet under favorable conditions (Glover, 1982).

A groundwater dam, shown in Figure 9, is another means of physical containment (Giddings, 1982). In order to abate leachate pollution at a landfill site, a groundwater dam of reworked clay till with alluvial backfill was constructed at the toe of the landfill. A perforated pipe underdrain was used to collect and transport leachate along the base of the dam. The advantages of this system were the creation of a tangible barrier to leachate flow and the formation of a positive containment wall. The leachate collected via the underdrain was recirculated to the landfill surface while contractual negotiations were ongoing in an effort to determine the possibility of discharging effluent into a nearby sewage system with or without pre-treatment.

Surface capping and lining are indirect methods of containing contaminated groundwater. They are often used in conjunction with other containment methods to minimize infiltration and leaching, and to prevent contamination by surface runoff. Surface capping and lining are described more fully in a following section dealing with source abatement.

PRODUCT RECOVERY

Recovery of contaminant products from groundwater for disposal or re-use is an important aspect of aquifer restoration projects. When facing a groundwater contamination incident, whether it is leachate from a waste dump, product leaking from storage tanks or pipelines, or chemicals from accidental spills such as train derailments, initial monitoring of the site, followed by spill containment procedures must be implemented.

Monitoring wells on site enable the determination of the type(s) of contaminant and characterization of the source (continuous point source or slug). The chemical and physical nature of the contaminant also must be determined immediately as it may affect the choice of recovery procedures and equipment. Is the contaminant volatile? Does it float on the water table? Is it miscible? Does it sink to the bottom of the aquifer? These are questions that must be answered during initial site assessment. These factors, as well as others such as the volume and extent of the spill, quantity of recoverable product, site hydrogeology, time frame for cleanup, environmental concerns and environmental regulations are necessary considerations in the selection of appropriate product-recovery systems (Quince, 1983). Quince (1983) has outlined recovery techniques under three categories: gravity collection, suction lift, and positive displacement.

In certain types of contaminant recovery operations, gravity collection procedures are the most suitable means of recovering the spilled product. Easily installed and requiring little maintenance, these systems are effective in areas of shallow groundwater flow in unconfined aquifers. Gravity collection is applied most commonly to leachate recovery from landfills and in the recovery of immiscible contaminants found on the groundwater surface (Quince and Gardner, 1982). Digging interceptor trenches or installing French drains down-gradient from the contaminant source to create a slight draw-down in the water table allows infiltration of contaminated groundwater into the trench or drain system (Quince and Gardner, 1982). The intercepted liquids are periodically pumped away so that the contaminant can be separated from the groundwater for disposal or treatment and re-use.

Gravity collection systems may be passive or active depending on the requirements of the recovery operation (Quince and Gardner, 1982). In an active system, groundwater migration rates are accelerated by increasing the hydraulic gradient by inducing drawdown or by artificial recharge. Passive gravity collection operations allow recovery to progress with little change in groundwater flow rates.

Trenches and French drains may be used to capture surface runoff along with groundwater. In a contamination incident reported by Winegardner and Quince (1984) in which a train derailment resulted in the leakage of several thousand gallons of a semi-soluble, aliphatic plasticizer compound, a French drain was used to capture surface runoff along with groundwater from which the contaminant was later removed. The system, along with a network of recovery wells, proved to be very effective at collecting the contaminant and limiting plume

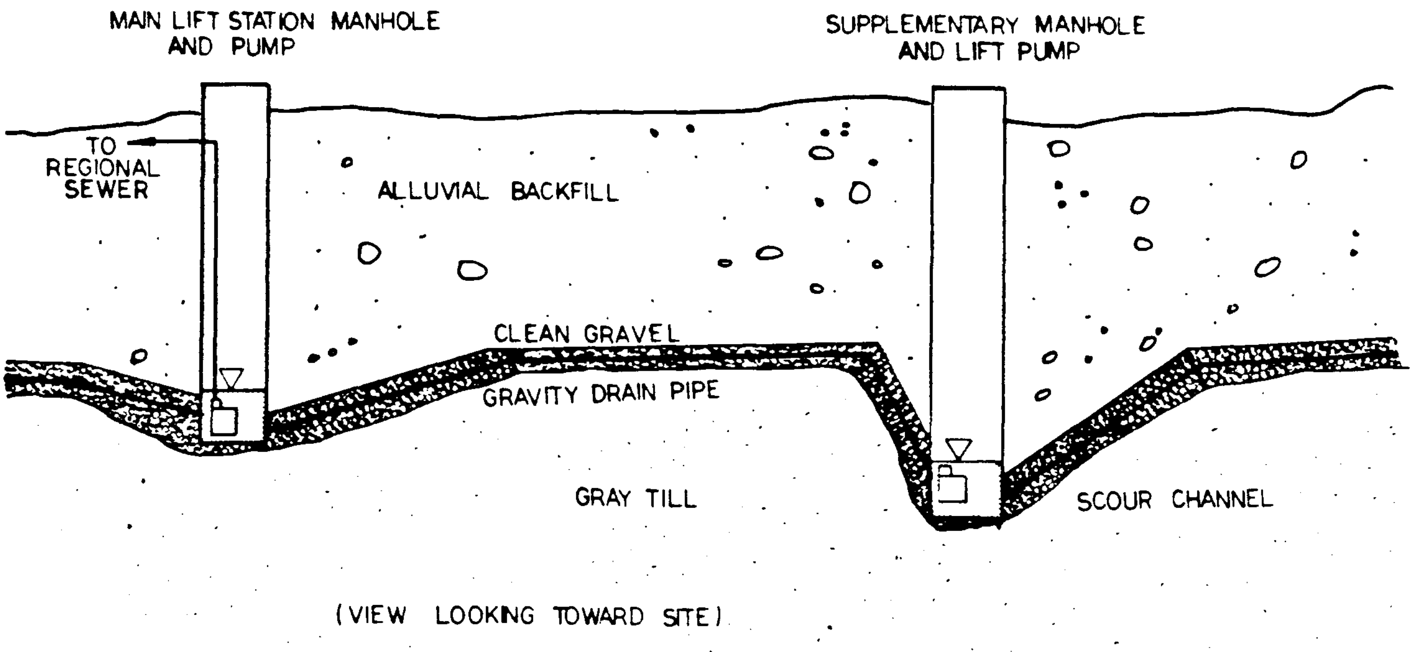

Figure 10. Longitudinal profile of gravity collection system (Giddings, 1982).

migration. Another gravity drain system, described by Giddings (1982), was effectively used to recover leachate at a landfill site (Figure 10). As part of the groundwater dam (refer to Figure 9, p. 18), this underdrain pipe installed in a gravel fill allowed infiltration of leachate downward into the permeable gravel overlying relatively impermeable gray till.

Trench-based systems, however, are often plagued with product emulsification problems and are subject to other difficulties (Yaniga, 1982). Problems encountered using trench-based systems include harmful fumes or flammable contaminants which could pose a greater danger when exposed in a trench.

Where gravity collection is not applicable, another alternative is the use of recovery wells. There are several types

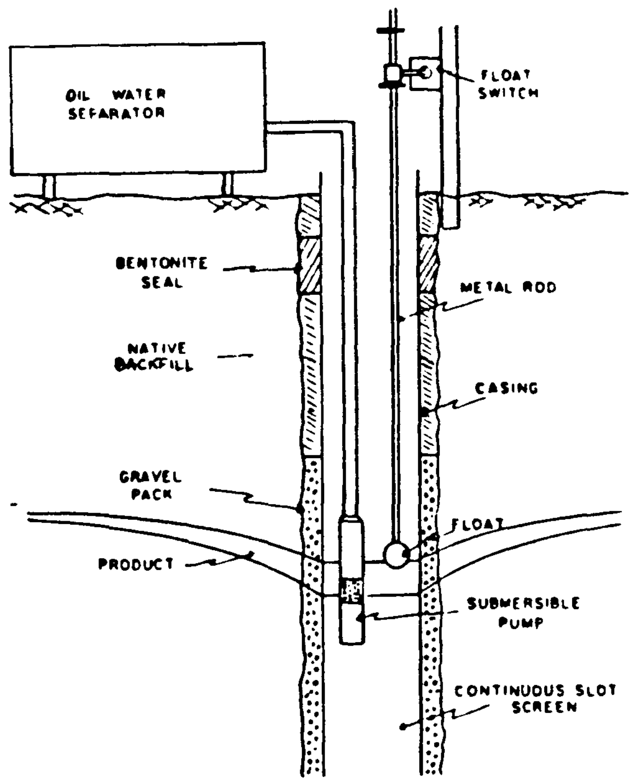

Figure 11. Schematic of one-pump system utilizing a submersible pump and float controls (Canter and Knox, 1985).

of recovery well systems which vary by the number of wells and the number of pumps utilized. Following are descriptions of several types of subsurface recovery systems used to recover hydrocarbons and other substances which float on the water table.

Suction-lift methods using one well and one pump (Figure 11) remove contaminated groundwater from the subsurface and pump it to product separators and treatment units. One pump connected to several recovery wells is another commonly applied technique. A disadvantage of one-pump systems is the need to separate the recovered mixture on the surface (Canter

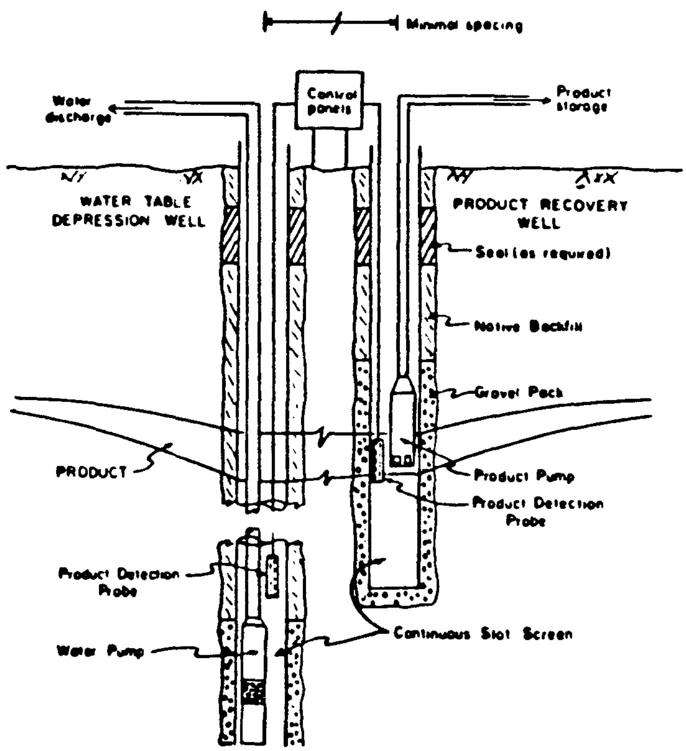

Figure 12. Schematic of two-pump system utilizing two small-diameter wells (Canter and Knox, 1985).

and Knox, 1985). Two-pump, two-well systems (Figure 12) use one well to create drawdown allowing the product to migrate toward an adjacent, second well to be recovered. This system enables separate recovery of groundwater and contaminant.

The preferred system of product recovery is that using two pumps in one well (Canter and Knox, 1985). Figures 13 and 14 show the operating principles of this type of recovery method. A lower pump creates a cone of depression which causes free product to migrate toward the second pump so that it can be brought up to the surface. Similar in principle to the two-well system, this method reduces drilling costs. Furthermore,

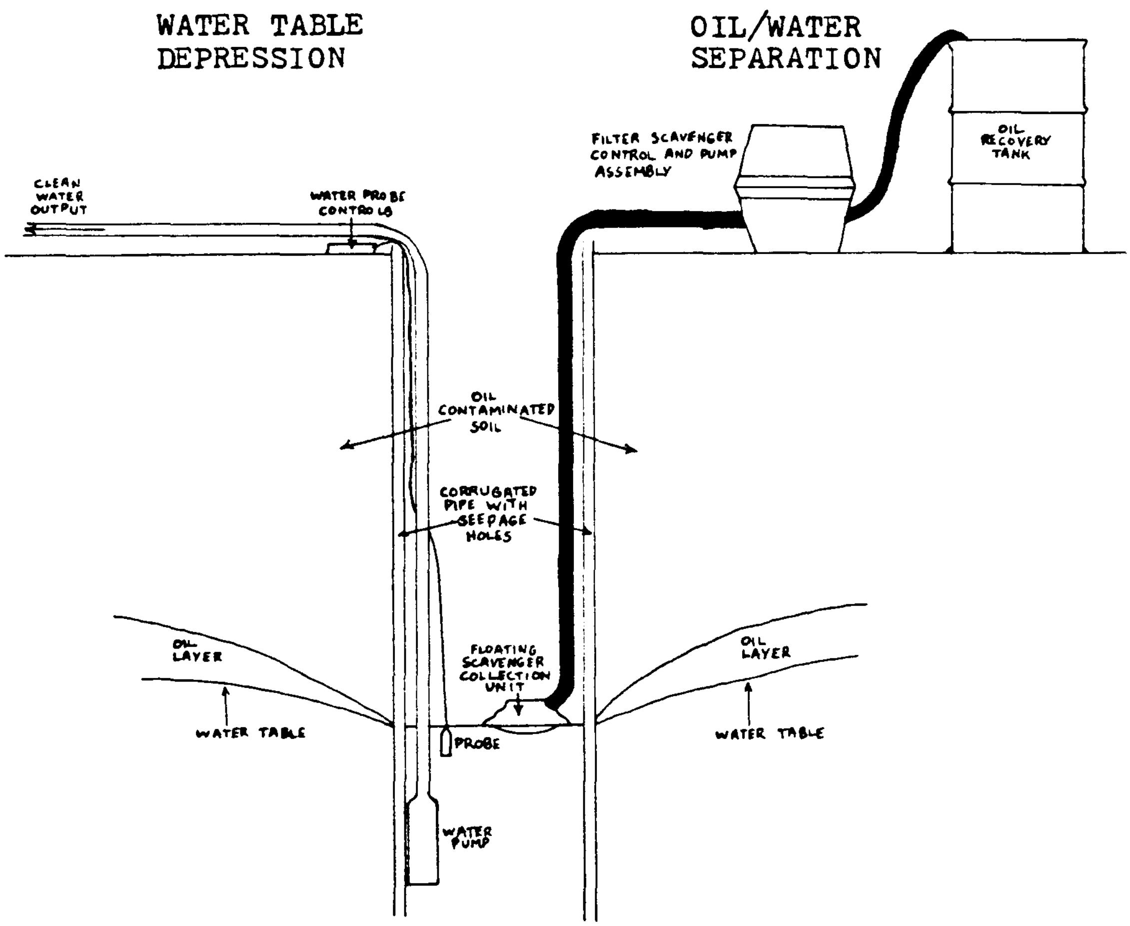

Figure 13. Hydrocarbon recovery using a water-table depression pump and a filter-scavenger collection unit (after Yaniga, 1982; Landon and Sylvester, 1982).

it lessens the need for product separation equipment.

Figure 15 illustrates the use of a skimmer device for contaminant recovery. A collection vessel is lowered into a recovery well to continually skim free product from the water-table surface. When full, the vessel is automatically retrieved and the recovered mixture is routed to a built-in oil/water separator.

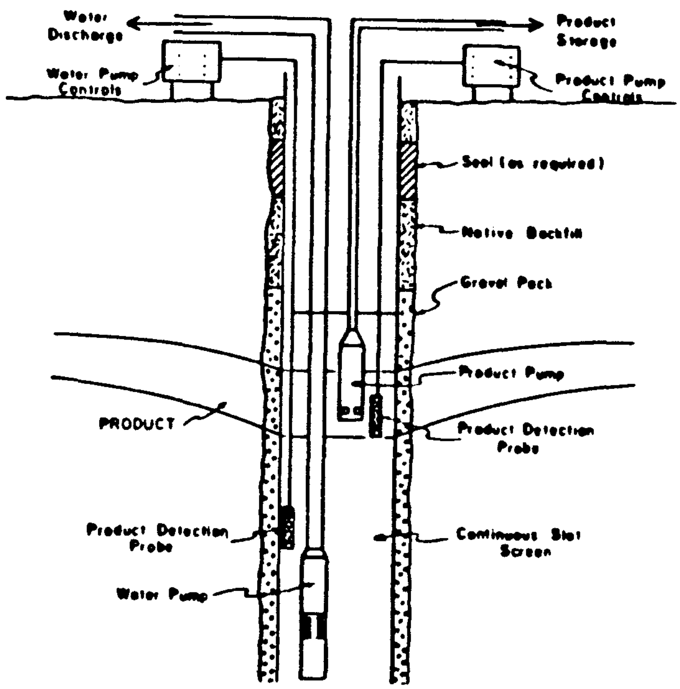

Figure 14. Schematic of two-pump system utilizing one recovery well (Canter and Knox, 1985).

In the case of contaminants which are heavier than water, other recovery methods must be devised. Winegardner and Quince (1984) discuss the use of a custom collection system to recover a viscous wood-preservative oil which had collected at the bottom of the aquifer over a period of many years. A large-diameter well was drilled 8 feet into the lower confining bed to create a sump effect. A probe operating on an electrical resistance basis sensed the rising of the contaminant in the sump and automatically started an above-ground pump which removed the oil. A slow, steady recovery rate was maintained by periodic pumping of the accumulating wood-preservative oil.

Operating Principle

1. The control mechanism automatically lowers a recovery vessel into the well until it has partially entered the liquid and becomes slightly buoyant.
2. The weight change resulting from the bouyancy causes the control mechanism to begin lowering the recovery vessel in a series of short pulses, pausing momentarily at each interval to permit the smooth skimming of free product over the slightly submerged rim of the vessel.
3. When the recovery vessel is approximately ¾ full, the unit mechanically senses its increased weight and automatically raises the vessel before it overfills.
4. Upon return of the recovery vessel to the surface, its contents are automatically pumped into the built-in oil/water separator from which the product is simultaneously pumped to a collection tank, and water is either returned to the well, or to surface disposal.

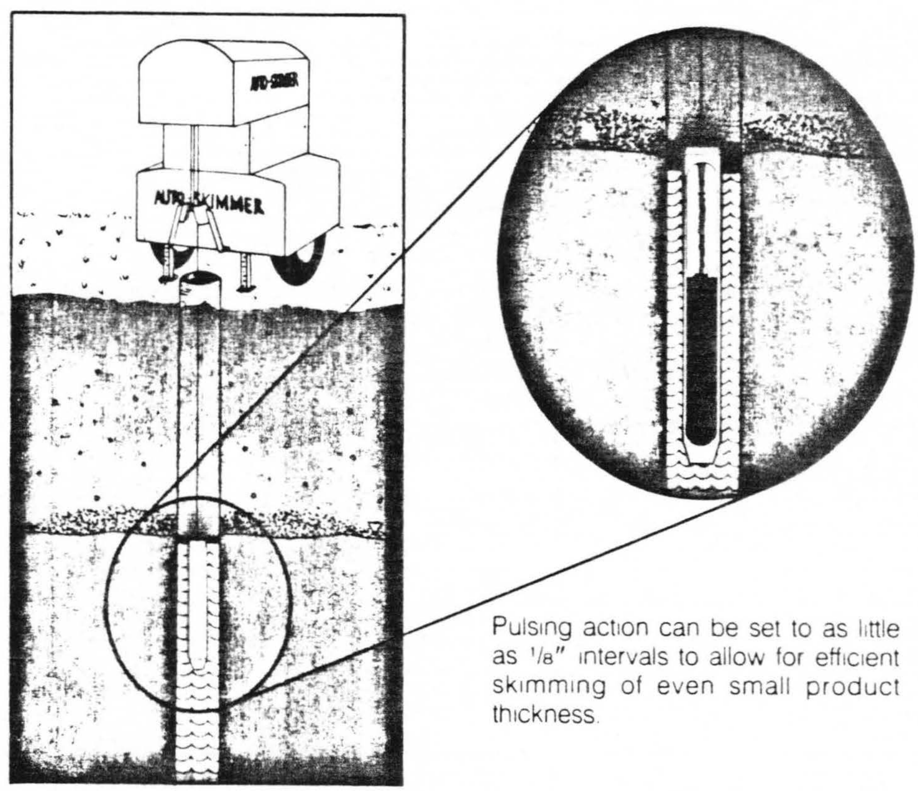

Figure 15. Hydrocarbon recovery using an automatic skimmer device (Wright, 1986).

In this case, 3,500 gallons of product were recovered after four months.

Often, product recovery is incomplete without artificially recharging the aquifer to flush out residual contamination and to increase groundwater flow towards recovery wells (Figure 16). Artificial recharge may be accomplished by surface application or by subsurface injection. Infiltration galleries also have been used successfully in artificial recharge

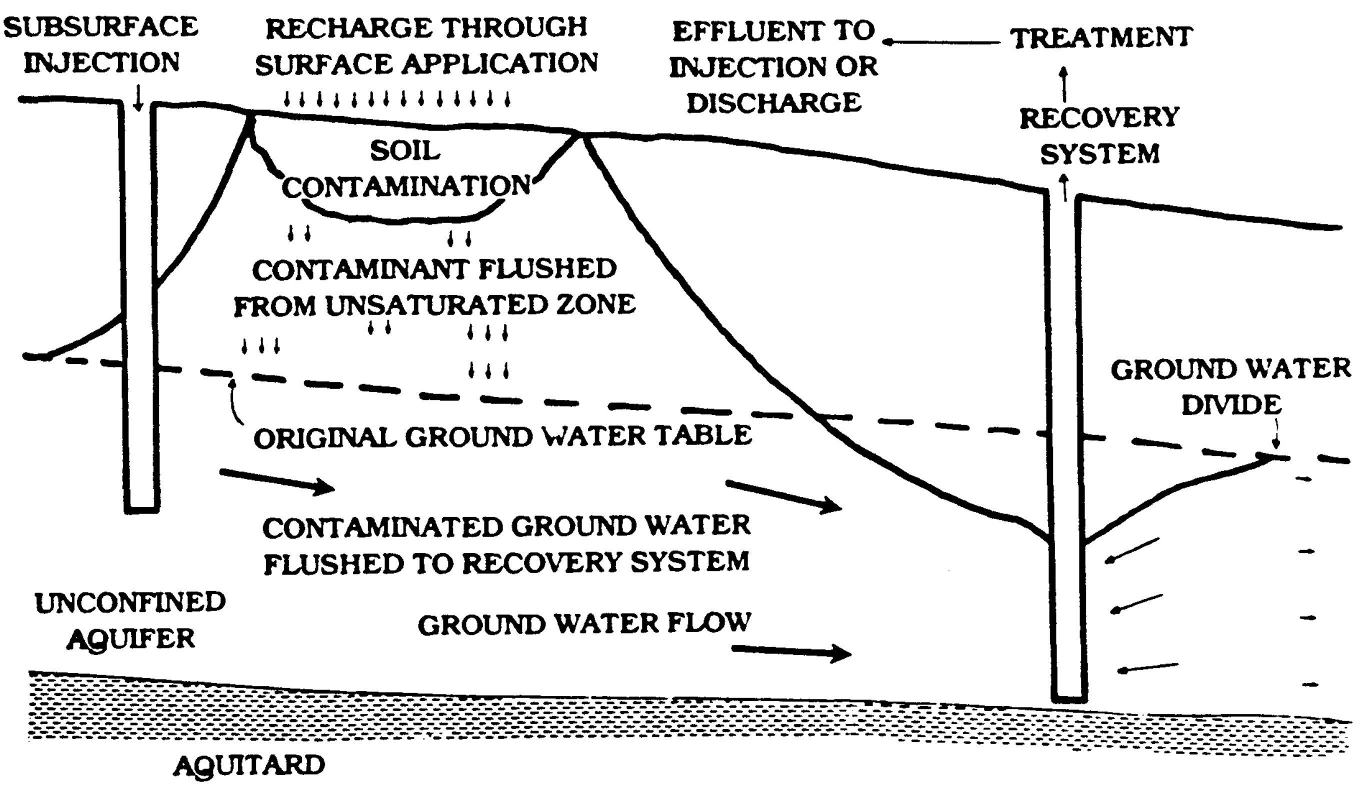

Figure 16. Schematic diagram of artificial recharge by subsurface injection and surface application used in the flushing of contaminants from groundwater (Quince and Gardner, 1982).

projects. Furthermore, as detailed in the following section, enhancement of recharge water with microorganisms or nutrients to create a "bio-reactor" in the subsurface permits acceleration of decontamination within the aquifer.

GROUNDWATER TREATMENT AND AQUIFER RESTORATION

The restoration of aquifer quality after impact by contaminants has become a subject of national concern. The first step in treatment and rehabilitation projects is free-product recovery which is described in the previous section. Actual treatment of contaminated groundwater can be divided into three primary classifications: physical, chemical, and biological.

Physical techniques involve phase separation and component separation. Oil separation and removal of suspended solids by filtration and/or settling are examples of phase separation. Component separation utilizes processes of adsorption, air stripping, ion exchange, and ultra-filtration to remove contaminants.

Chemical treatment involves the addition of a reactive material to the contaminated water to destroy or detoxify hazardous components. Types of chemical treatment are neutralization through pH adjustments, precipitation by adding flocculants, and oxidation/reduction reactions. Chemical treatment methods are normally applied to remove metals or neutralize corrosive chemicals.

Biological treatment methods consist of enhancing microbiological activity in the subsurface to convert toxic contaminants into non-toxic by-products (Quince and Gardner, 1982). This is accomplished by temperature adjustment, adding dissolved oxygen, adding nutrients, or introducing bacterial strains.

The following discussion covers air stripping, carbon adsorption, biodegradation, and in-situ natural treatment methods. Four types of air stripping technologies are in common use (Figure 17). They are: diffused aeration, countercurrent packed columns, cross-flow towers and coke-tray aerators (Canter and Knox, 1985). Diffused aeration basins are similar to wastewater treatment aeration basins and are used to remove volatile organic compounds. Coke-tray aerators allow impure water to trickle down through several trays to increase the surface area of the water to provide more efficient aeration. In countercurrent packed columns, contaminated water flows downward over a packing material as air flows upward. Cross-flow towers operate on the same basic principle as countercurrent packed columns with the addition of fans to force the air flow.

Canter and Knox (1985) indicate that countercurrent packed columns are the most appropriate means for treating contaminated groundwater because they provide the most liquid-air interfacial area, they make possible higher air-to-water volume ratios due to low air pressure through the column, and they are easily connected to vapor recovery equipment for removal of stripped volatile organics.

Figure 18 illustrates an air stripping pilot plant described by Weinstein (1982). This particular system is

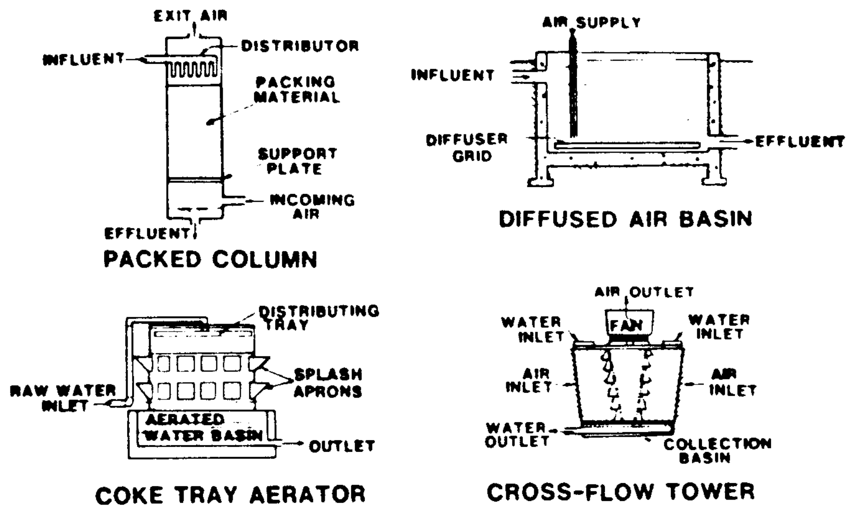

Figure 17. Air stripping equipment configurations (Canter and Knox, 1985).

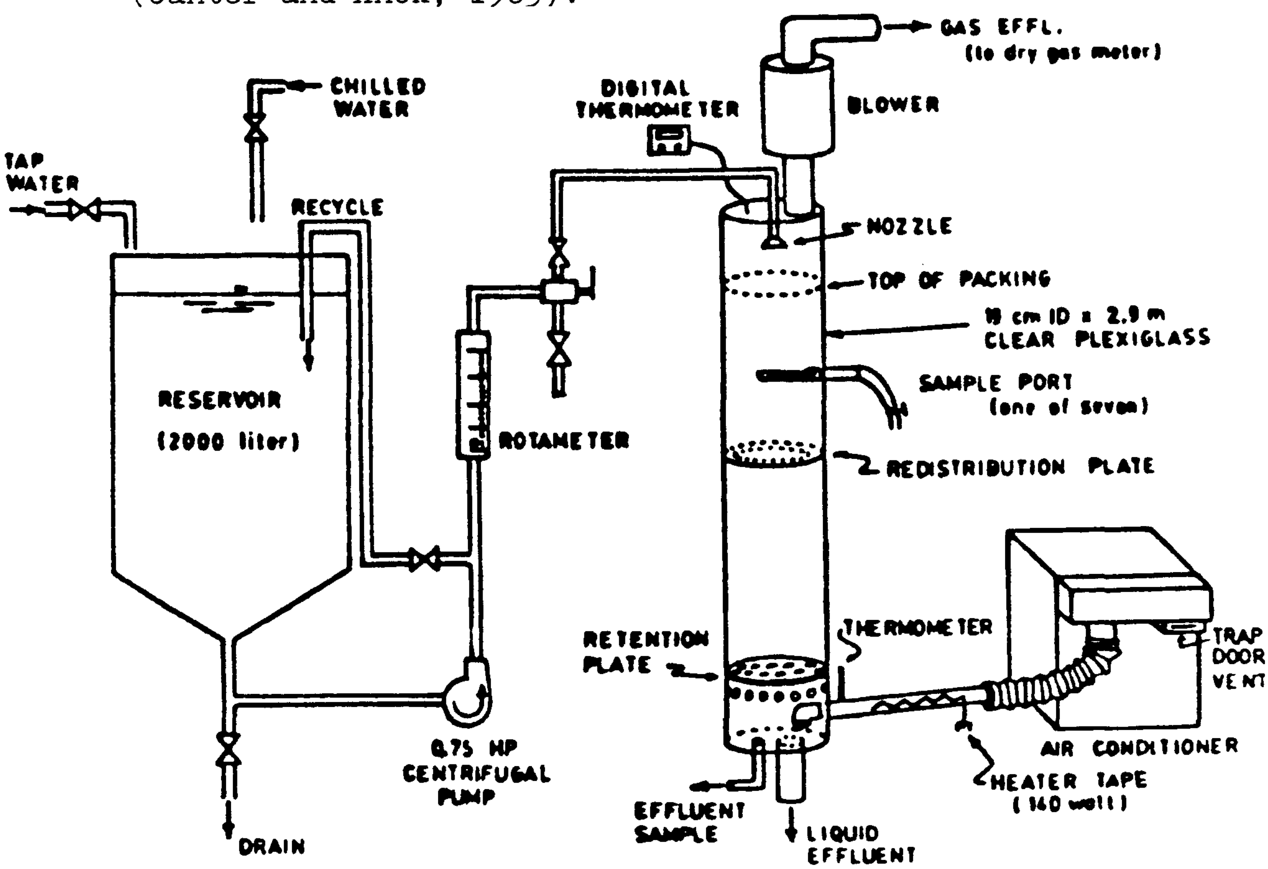

Figure 18. Air stripping pilot plant (Weinstein, 1982).

a packed-column type designed for cleanup of groundwater contaminated by 1,1,1-trichloroethane. The actual air stripping plant achieved excellent results by removing 99.9% of the organic contaminant.

Carbon-adsorption treatment consists of two contacting systems: fixed bed (Figure 19) and countercurrent moving beds (Figure 20). Fixed beds utilize downflow or upflow of water over fixed beds of activated carbon. In a fixed-bed system, suspended solids accumulate on the beds so that they must be periodically removed and backwashed before re-use. Moving beds operate using an upflow of water counter to the gravity downflow of activated carbon. The waste-contaminated groundwater enters the bottom of the column through a manifold system which uniformly distributes the flow. The water flows upward past a discontinuous, pulsed release of carbon until it reaches the top where it is withdrawn and transported to a second treatment column. Two or more columns are usually connected in series. A variation of this method is the fluidized bed consisting of a bed of activated carbon particles which become suspended as water flows upward through the bed. This is a great advantage over fixed-bed systems since the solids pass through without clogging the bed.

Biological treatment methods use living organisms to break down waste materials by natural biochemical processes. Techniques include activated sludge, aeration lagoons, trickling filters, anaerobic digestion, composting, and waste

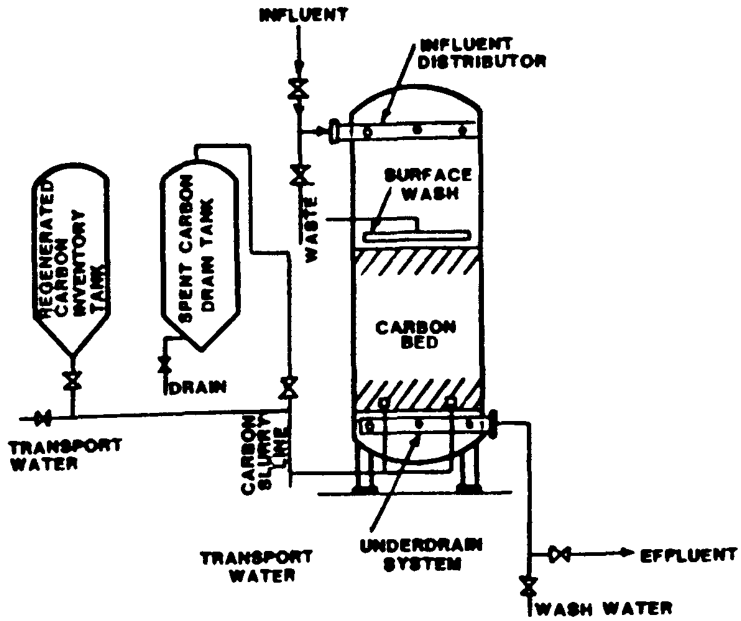

Figure 19. Fixed-bed adsorption system (Canter and Knox, 1985).

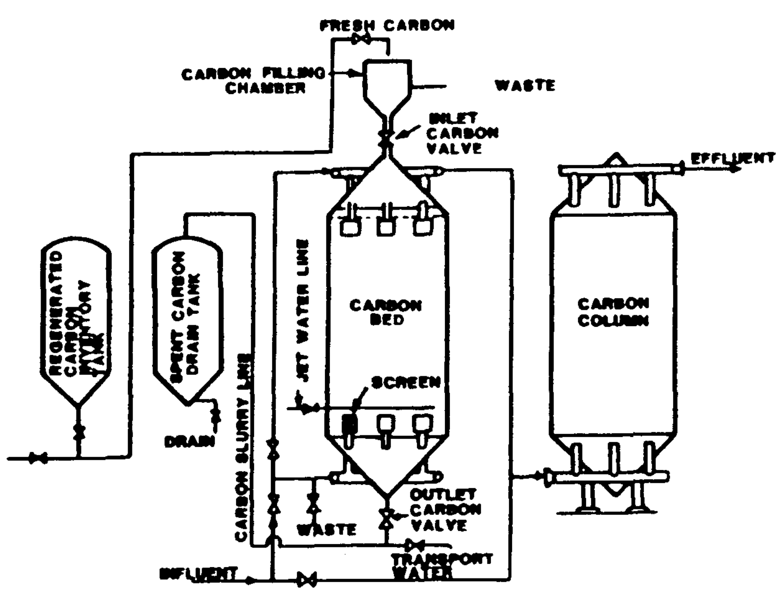

Figure 20. Moving-bed adsorption system (Canter and Knox, 1985).

stabilization (Quince and Gardner, 1982).

In-situ bio-stimulation techniques operate in two ways: by enhancement of indigenous microorganism populations, and by the addition of acclimated microorganisms into the aquifer to degrade contaminants. Yaniga and others (1985) describe a case in which accelerated, in-situ natural biodegradation was used to restore an aquifer contaminated by hydrocarbons. The biodegradation project was accomplished by a program which introduced inorganic nutrients and oxygen into a shallow aquifer and a deeper water-supply aquifer to accelerate natural degradation of hydrocarbons by indigenous species. The entire project consisted of withdrawal, treatment, and recharge to effectively remedy a groundwater contamination incident (Figure 21). The components of this treatment system included a centralized pumping well to contain contaminants and induce flow to recovery wells, an air-stripping tower, an infiltration gallery to recharge treated water and introduce nutrients, air compressors to reoxygenate the groundwater, subsurface oxygen-addition wells and nutrient-addition wells to stimulate biodegradation, and a regular monitoring program developed to safeguard a nearby residential area (Yaniga and others, 1985).

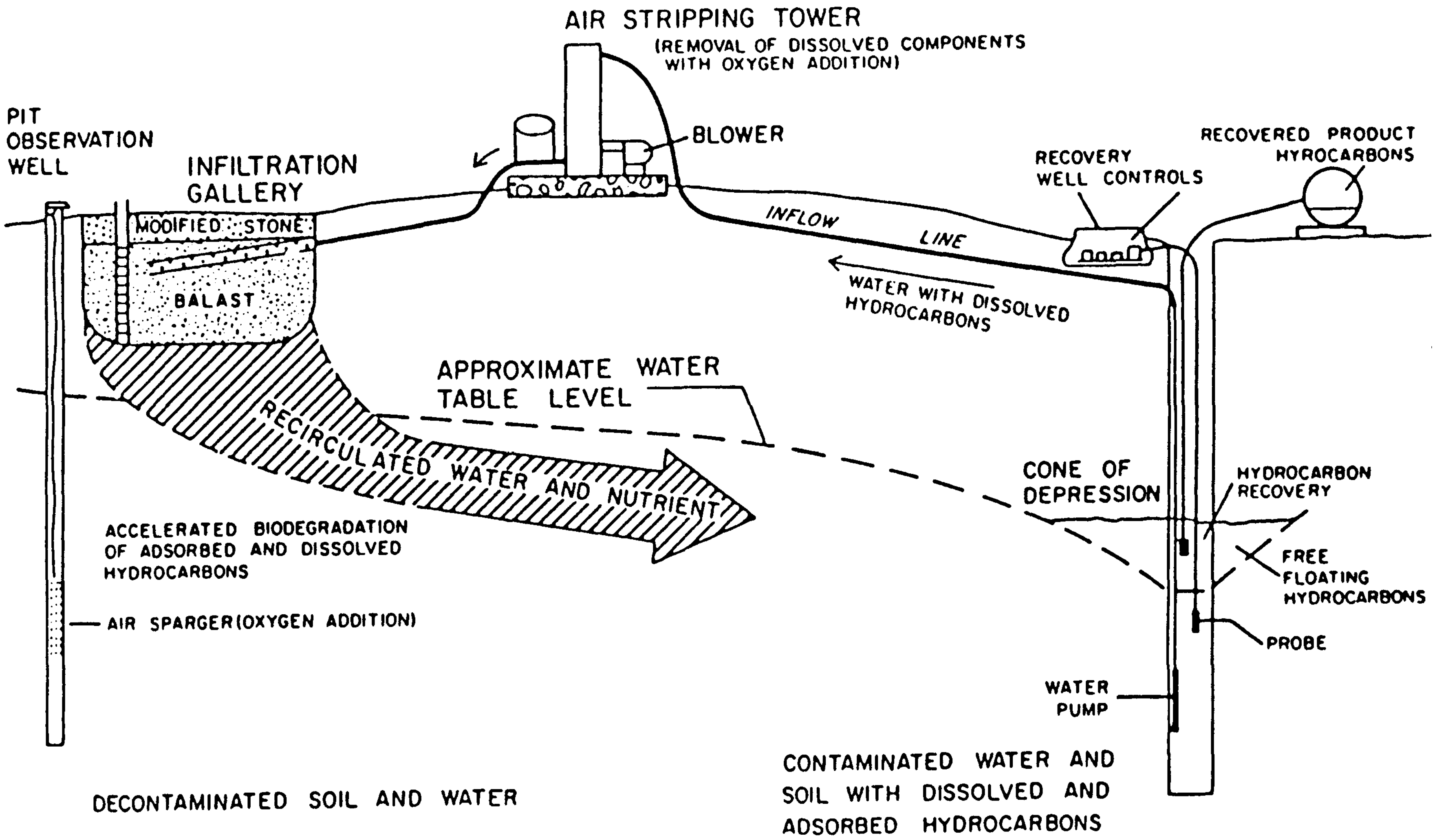

Figure 21. Cross section of an aquifer restoration project utilizing in situ biodegradation of the organic contaminants (Yaniga and others, 1985).

SOURCE ABATEMENT

A part of any remedial action program at a hazardous-waste site or contaminant-spill site is the removal of the source or sources of pollution. It is very important to remove the contaminant source to ensure that the groundwater is no longer being polluted and to enable aquifer rehabilitation measures to proceed. Once the source of escaping product is identified, the flow of pollutants must be stopped. In the case of an emergency spill, such as a train derailmant or truck accident, source removal is fairly straightforward. Other cases, such as waste disposal lagoons or drum disposal areas require more complex source removal techniques which are time consuming, and often hazardous.

Methods providing temporary containment of pollution sources are surface capping, liners, and surface-water diversion (Canter and Knox, 1985). Diverting surface water by means of drainage ditches is an inexpensive way of preventing leachate from migrating into the groundwater.

Capping and lining are often used in combination at waste sites to control downward flow of leachate and to reduce leachate production (Canter and Knox, 1985). One combination uses an impermeable liner with no surface cap in order to maximize leachate collection and prevent its escape into the aquifer. Another type of cap and liner combination uses an impermeable cap and no liner to increase surface runoff and minimize downward infiltration through the waste source. A third combination uses both an impermeable cap and an impermeable liner to minimize infiltration and maximize leachate collection.

For contamination resulting from leaking underground storage tanks, such as gasoline storage tanks, the alternatives in source abatement are tank repair or replacement. Although expensive, replacement of corroded steel tanks with fiberglass tanks is the preferred alternative.

Often, contaminated soil must be excavated and disposed of off-site because of the danger of leaching of chemicals in the soil. A case described by Reuter and others (1983) involving a spill of 200 drums of assorted waste chemicals including benzene, chloroform, and toluene required the removal of contaminated soil. Six to 12 inches of soil were scraped from the site and stockpiled on polyethylene sheeting to prevent leached chemicals from infiltrating into the ground. The soil stockpiles also were covered with the polyethylene material. Later, the soil was removed for safe disposal. This method proved quite effective at preventing downward flow of the chemicals so that aquifer restoration could proceed.

The suitability of source removal alternatives at any given site is determined by consideration of site characteristics, contaminant characteristics, and whether removal is to be temporary or permanent.

GROUNDWATER MONITORING

As mentioned previously, site-specific groundwater studies normally include geologic mapping, test borings, and other field testing. Concurrent with or subsequent to site-specific investigation, monitoring facilities are installed upgradient from a site to determine ambient water quality and downgradient to delineate the contaminant plume (Glover, 1982). The objective of a monitoring program at a contaminant spill area is to define the direction and velocity of groundwater flow, the areal extent of contaminant plumes, to determine contaminant concentrations, and to define necessary groundwater controls needed to limit further migration of product and enable recovery of that product (Yaniga,1982). Regular groundwater monitoring is done to detect contaminants entering into the groundwater as well as to delineate the contaminants once they reach the groundwater. At a contaminated site, monitoring gives an indication of physical changes caused by injection/recovery systems, hydrodynamic barriers, and the entire restoration project itself (Quince and Gardner, 1982). Monitoring-well networks should encompass not only the zone influenced by an aquifer restoration project, but also the area outside the perimeter of the affected area.

In order to adequately monitor and sample contaminated groundwater, monitoring wells must be installed with careful consideration of several factors. These include proximity

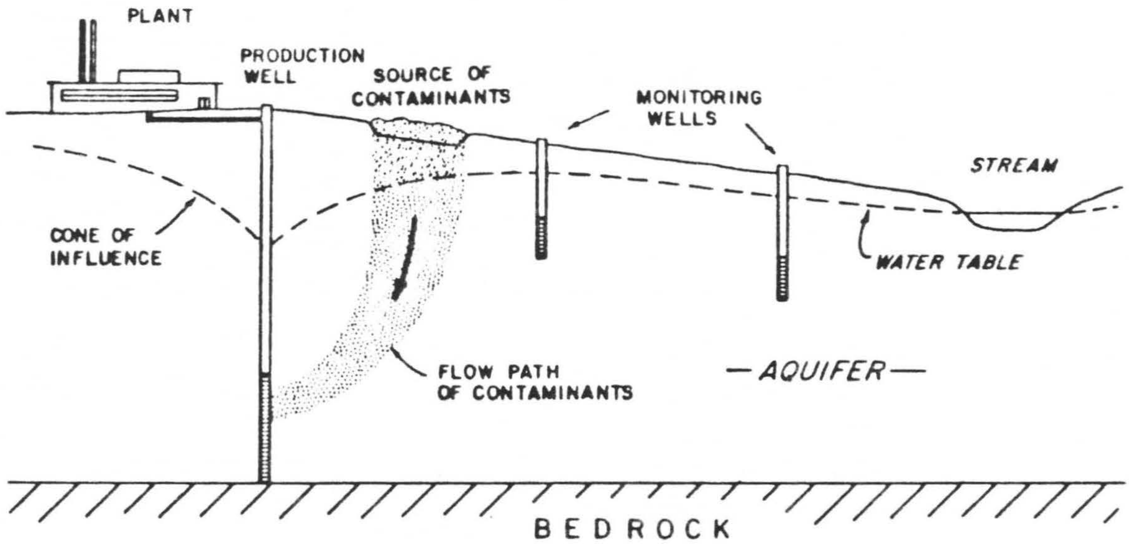

Figure 22. Monitoring wells placed at lower topographic elevations in the direction of natural groundwater flow may not be effective if contaminants are captured by the cone of influence of a nearby pumping well (Miller, 1984).

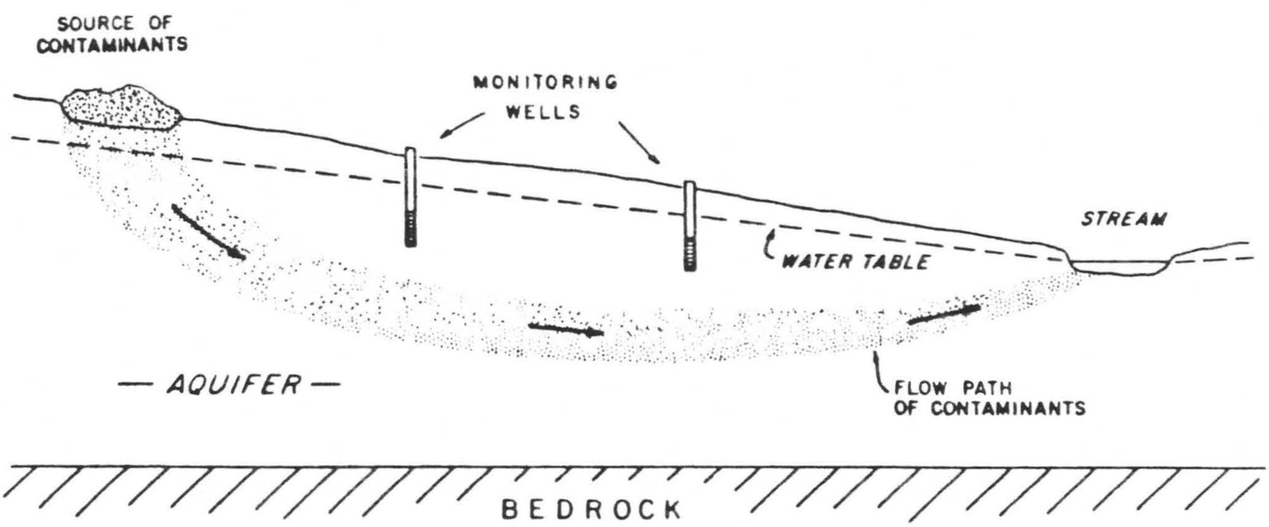

Figure 23. Monitoring wells screened in the upper part of the zone of saturation may not detect contaminants moving through a lower section of the aquifer (Miller, 1984).

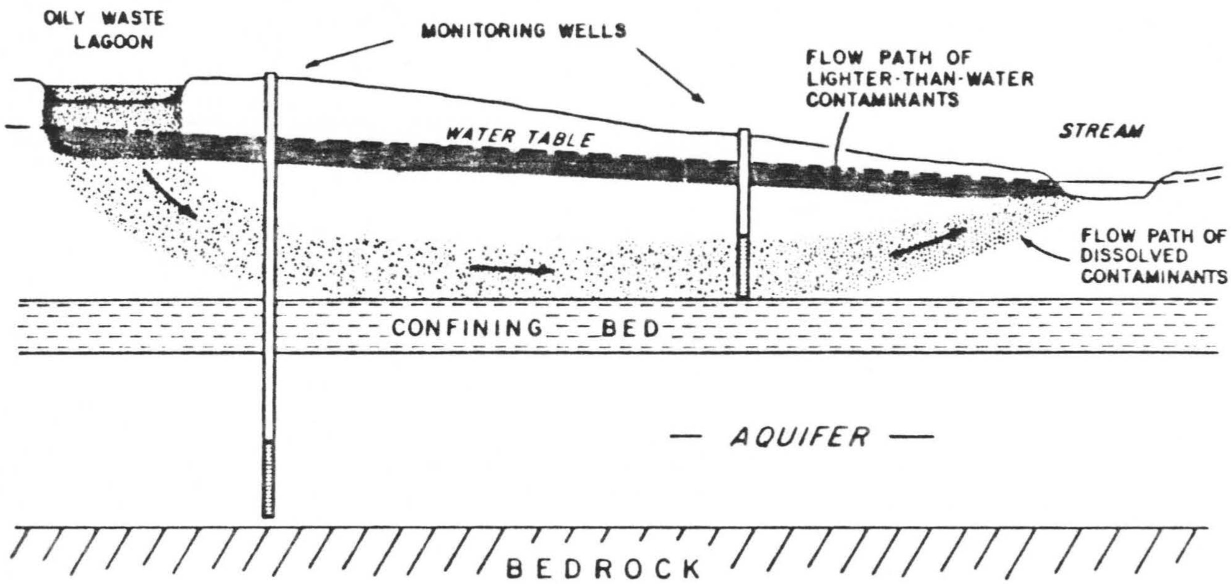

Figure 24. Monitoring wells screened in a lower aquifer or in the plume of dissolved contaminants may not detect lighter-than-water components of contamination (Miller, 1984).

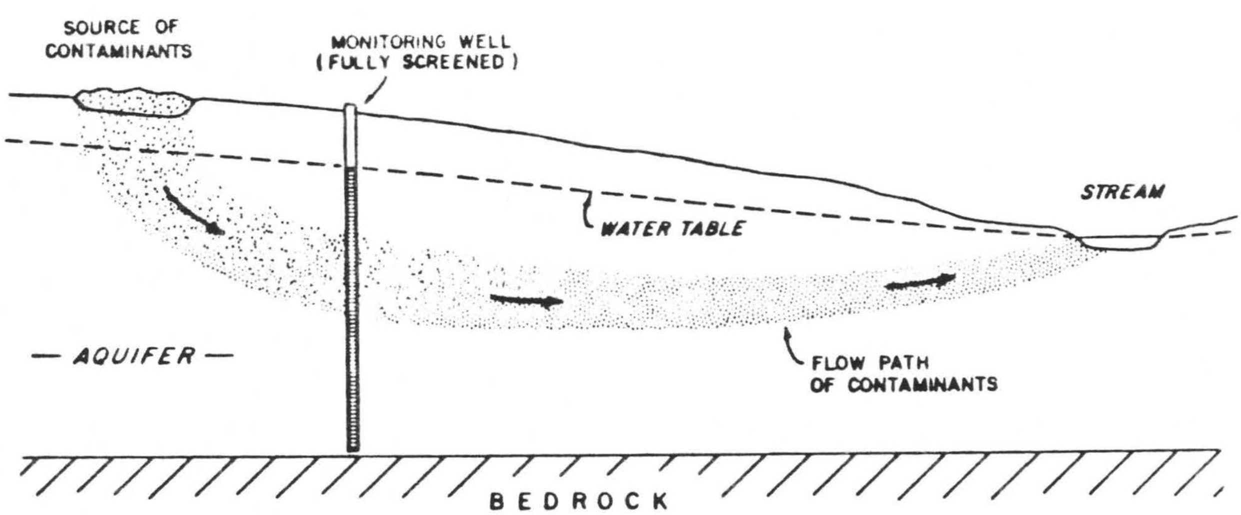

Figure 25. Samples from monitoring wells screened through the entire zone of saturation may yield a mixture of contaminated water diluted with clean water from unaffected sections of the aquifer (Miller, 1984).

of pumping wells, screen placement and length, and contaminant characteristics. Figure 22 demonstrates the problem that would be encountered if a pumping well's cone of influence captures a contaminant plume. Figures 23, 24, and 25 depict

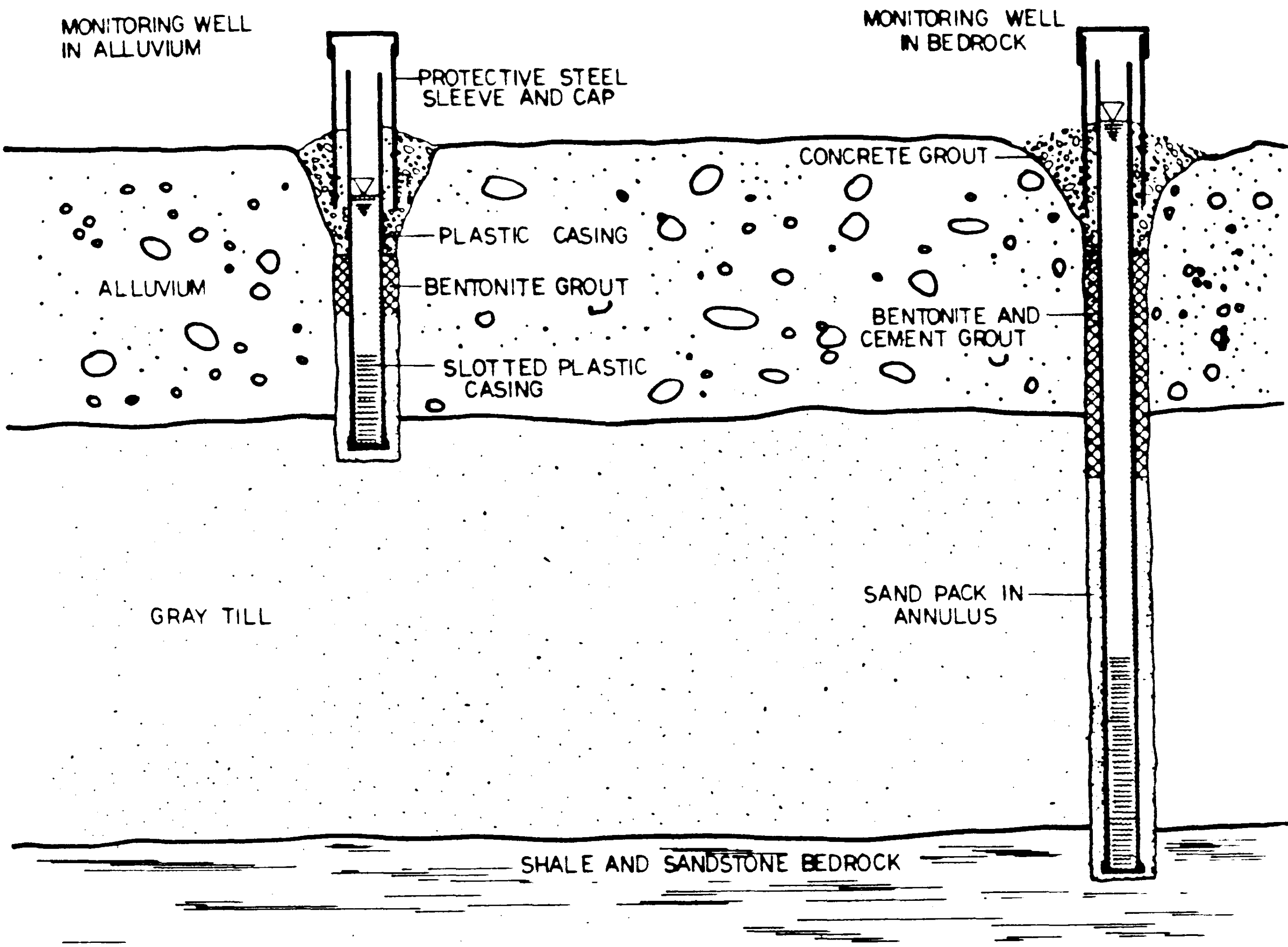

Figure 26. Typical monitoring well construction (Giddings, 1982).

other problems encountered with improperly installed monitoring wells. Figure 26 shows a typical monitoring system designed to monitor leachate movement at a landfill site.

Monitoring wells should be placed so that samples may be taken from different areas, both laterally and vertically, in the aquifer to give a correct indication of subsurface conditions. Correct and complete monitoring is necessary before contamination becomes a problem and after product has reached the groundwater. Groundwater monitoring is an essential part of an aquifer rehabilitation program. Monitoring networks serve as warning systems should containment systems fail and contaminants threaten usable groundwater supplies.

CONCLUSION

As concern for preserving groundwater quality increases, technology which prevents contamination and technology which enables restoration of water quality need to be evaluated and utilized. A review of recent case studies showing the application of techniques currently used to remedy groundwater contamination incidents reveals the successful use of available methods to abate pollution sources and restore groundwater quality. A necessary part of remedial action programs is the development of a carefully evaluated plan of action. Important considerations include hydrogeologic investigation, contaminant plume isolation methods, product or leachate recovery systems, groundwater treatment and aquifer restoration methods, source elimination procedures, and groundwater monitoring. All of the above must be evaluated in any aquifer restoration project.

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